

R-parity violation in  $(t + \bar{t})\tilde{g}$  production at LHC and Tevatron \*M. Chaichian<sup>a,b</sup>, K. Huitu<sup>a</sup> and Z.-H. Yu<sup>a,b</sup><sup>a</sup>Helsinki Institute of Physics<sup>b</sup>Department of Physics, University of Helsinki

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## ABSTRACT

We study the production of  $(t + \bar{t})\tilde{g}$  at the hadron colliders in an R-parity ( $R_p$ ) violating supersymmetric model. This process provides us with information not only about  $R_p$  violation, but may also help us in detecting the supersymmetry itself. It is possible to detect an  $R_p$  violating signal (with single gluino production) at the future hadron colliders, such as Fermilab Tevatron Run II or CERN Large Hadron Collider (LHC), if the parameters in the supersymmetric  $\mathcal{R}_p$  interactions are not too small, e.g. for  $m_{\tilde{g}} = 1$  TeV,  $\lambda'' = 0.1$ , still hundreds of events are produced at LHC with luminosity  $30 \text{ fb}^{-1}$ . Even if we could not detect a signal of  $\mathcal{R}_p$  in the experiment, we get stringent constraints on the heavy flavour  $\mathcal{R}_p$  couplings. In addition to the minimal supersymmetric standard model we have also considered some models with a heavy gluino as the lightest supersymmetric particle.

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## I. Introduction

It is well known that the minimal supersymmetric standard model (MSSM) [1] in its most general form contains lepton number ( $L$ ) and baryon number ( $B$ ) violating couplings. The resulting catastrophic proton decay [2] can be avoided by imposing R-parity symmetry  $R_p$ ,

$$R_p = (-1)^{3B+L+2S}, \quad (1)$$

where  $S$  is the spin of the particle. In the models with R-parity conservation, superparticles can only be pair produced and the lightest supersymmetric particle (LSP) will be stable. However,  $R_p$  conservation is not necessary for forbidding proton decays, instead of that, we just need either B-conservation or L-conservation [3]. Models with  $R_p$  violation ( $\mathcal{R}_p$ ) can provide many interesting phenomena, such as neutrino masses and mixing. Partly because of that,  $\mathcal{R}_p$  has attracted much attention [4, 5, 6]. Many constraints from low-energy phenomenology [6] are collected in Ref. [7].

The supersymmetry (SUSY) must be broken, since it has not been observed so far. Two kinds of breaking mechanisms of supersymmetry have been extensively studied phenomenologically, namely the minimal supergravity (mSUGRA) [8] and minimal gauge-mediated SUSY breaking (GMSB) [9]. These predict a different pattern of masses especially for the partners of gauge bosons, gauginos. Thus, finding the signals of gauginos is an important way to probe SUSY. In mSUGRA and GMSB, it is assumed that masses of gauginos will be unified at Grand Unified Theory (GUT) scale. From the evolution of parameters, gluinos should be the heaviest gauginos at low scale, since the ratios of gaugino masses to coupling constants do not change with scale in one-loop approximation [10]. Thus gluinos can decay to other gauginos with jets in the  $R_p$ -conserving model [11].

However, heavy gluino as LSP (or NLSP) may still exist in some GMSB models, as S. Raby suggested in [12]. He introduced the Higgs-Messenger mixing in GMSB model. This would lead triplet-doublet messengers split from triplet-doublet Higgs splitting. Since gluino obtains mass from SUSY-breaking induced by triplet messengers, heavier triplet messengers could suppress the mass of gluino so that gluino could be the LSP (or NLSP). The experimental limits on the masses of gluinos have been discussed in  $R_p$ -conserving model [13]. In  $R_p$ -violating model, gluinos can decay through  $R_p$ -violating channels, which obviously changes both the detection strategy and present mass limits [14].

In the high energy hadron colliders especially squarks and gluinos will be produced plentifully, if they are not too heavy. It is hoped for that information on SUSY is found in Fermilab Tevatron Run II, or in the future CERN Large Hadron Collider, where squarks and gluinos with masses below 1.5 TeV should be detected [15]. In mSUGRA and GMSB models, masses of squarks and gluinos are usually of the same order. However, in some special mechanism, such as O-II model [16], it has been suggested that squarks can be much heavier than gauginos. In this model the gluinos will be produced at much lower energies than squarks, so that it can be the first detected SUSY particle at hadron colliders. Since gluinos would be almost degenerate with the lightest neutralino and chargino,  $R_p$  violating decay of gluinos will be significant [7].

The single production of gluinos, neutralinos and charginos has already been considered in the general case [17], and the single production of squarks, which is also significant to detect SUSY and  $R_p$ -violation, has been considered recently [18]. In this work we will consider  $\mathcal{R}_p$  at hadron colliders in the process

$$PP(P\bar{P}) \rightarrow t + \tilde{g} (\bar{t} + \tilde{g}). \quad (2)$$

This process occurs via B-violating terms in the  $\mathcal{R}_p$  model. In terms inducing heavy flavours, the  $\mathcal{R}_p$  couplings can be very large from the present upper limits [7]. For example,  $\lambda''_{2ij}$  and  $\lambda''_{3ij}$ , getting their strongest constraints from the ratio of widths of  $Z$  to leptons and hadrons, can be of order one ( $\mathcal{O}(1)$ ) for the sfermion mass  $\mathcal{O}(100 \text{ GeV})$ .

The pair production and decay of gluinos at hadron colliders have already been researched in Ref. [19]. It has been shown that detecting gluinos is very difficult. It may become easier with an accompanying top quark in the process which we consider.

On the other hand, the single top quark production is an interesting topic itself [20]. The single top quark production in the  $\mathcal{R}_p$  model has been considered in Ref. [21]. There, the possible cross section will depend on the  $\mathcal{R}_p$  parameters as  $|\lambda''|^4$ , while the process we will consider depends on  $|\lambda''|^2$ . Although the mass of the gluino is not known presently, it is still possible to get stronger constraints on  $\mathcal{R}_p$ -violating parameters from the  $(t + \bar{t})\tilde{g}$  production.

In the following, we will give the analytical calculations of  $PP(P\bar{P}) \rightarrow t\tilde{g}(\bar{t}\tilde{g})$  in section II. In section III gluino and top decays are considered and in section IV the numerical results are presented. The conclusions are given in section V and some details of the expressions are listed in the appendix.

## II. Production of gluinos in $PP \rightarrow t\tilde{g}$

The superpotential for  $\mathcal{R}_p$  violating, but gauge and supersymmetry preserving interactions is written as [6]

$$W_{\mathcal{R}_p} = \lambda_{[ij]k} L_i \cdot L_j \bar{E}_k + \lambda'_{ijk} L_i \cdot Q_j \bar{D}_k + \lambda''_{i[jk]} \bar{U}_i \bar{D}_j \bar{D}_k + \epsilon_i L_i H_u \quad (2.1)$$

where  $L_i$ ,  $Q_i$  and  $H_u$  are SU(2) doublets containing lepton, quark and Higgs superfields respectively,  $\bar{E}_j$  ( $\bar{D}_j$ ,  $\bar{U}_j$ ) are the singlet lepton superfields (down-quark and up-quark). The square brackets around the generation indices  $i, j$  denote antisymmetry of the bracketted indices.

We ignored the last term in Eq. (2.1) because its effects are assumed small in our process [7]. Thus, we have 9  $\lambda$ -type, 27  $\lambda'$ -type and 9  $\lambda''$ -type independent parameters left. The constraints on the couplings [7],

$$|(\lambda \text{ or } \lambda')\lambda''| < 10^{-10} \left( \frac{\tilde{m}}{100 \text{ GeV}} \right)^2. \quad (2.2)$$

is usually taken to indicate that only L- or B-number violating couplings exist.

In our work we will only consider the baryon number violating couplings, i.e., the third term in Eq. (2.1). In the following calculations we assume the parameters  $\lambda''$  to be real.

We define the Mandelstam variables as usual

$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2, \quad (2.3.a)$$

$$t = (p_1 - p_3)^2 = (p_4 - p_2)^2, \quad (2.3.b)$$

$$u = (p_1 - p_4)^2 = (p_3 - p_2)^2. \quad (2.3.c)$$

The amplitude (Feynmann diagrams in Fig.1) of  $q_j q'_k \rightarrow \bar{t}\tilde{g}$  is given by:

$$M = M_s + M_t + M_u, \quad (2.4)$$

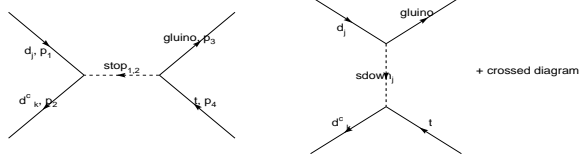


Figure 1: Feynman diagrams of  $q_j q_k \rightarrow \bar{t} \tilde{g}$ .

with

$$\begin{aligned}
M_s = & \bar{u}^a(p_3)(-i\sqrt{2}g_s T_{\alpha\alpha'}^a)(\cos\theta P_L + \sin\theta P_R)v_{\alpha'}(p_4)\frac{i}{(s-m_{\tilde{t}_1}^2+im_{\tilde{t}_1}\Gamma_{\tilde{t}_1})} \\
& \times \bar{v}_\gamma^c(p_2)(2i\epsilon^{\alpha\gamma\beta}\lambda_{3kj}'')\sin\theta P_R u_\beta(p_1) \\
& + \bar{u}^a(p_3)(-i\sqrt{2}g_s T_{\alpha\alpha'}^a)(\sin\theta P_L - \cos\theta P_R)v_{\alpha'}(p_4)\frac{i}{(s-m_{\tilde{t}_2}^2+im_{\tilde{t}_2}\Gamma_{\tilde{t}_2})} \\
& \times \bar{v}_\gamma^c(p_2)(-2i\epsilon^{\alpha\gamma\beta}\lambda_{3kj}'')\cos\theta P_R u_\beta(p_1),
\end{aligned} \tag{2.5.a}$$

$$M_t = \bar{u}^a(p_3)(i\sqrt{2}g_s T_{\beta\rho}^a P_R)u_\rho(p_1)\frac{i}{(t-m_{\tilde{d}}^2)}\bar{u}_\alpha^c(p_4)(-2i\epsilon^{\alpha\beta\gamma}\lambda_{3jk}'')P_R u_\gamma(p_2), \tag{2.5.b}$$

$$M_u = \bar{u}^a(p_3)(i\sqrt{2}g_s T_{\beta\gamma}^a P_R)u_\gamma(p_2)\frac{i}{(u-m_{\tilde{d}}^2)}\bar{u}_\alpha^c(p_4)(-2i\epsilon^{\alpha\beta\rho}\lambda_{3kj}'')P_R u_\rho(p_1), \tag{2.5.c}$$

where  $P_{L,R}$  are left- and right-helicity projections respectively,  $\theta$  is the mixing angle of stop quarks (see Appendix for details) and  $\Gamma_{\tilde{t}_{1,2}}$  are decay widths of stop quarks  $\tilde{t}_{1,2}$ . The families of down-type quarks are marked by  $j, k = 1, 2, 3$  and the upper index  $c$  means charge conjugate. In the calculations, we have neglected all mixing angles of scalar quarks except stop quarks. The amplitude depends on the  $R_p$ -violating parameters  $\lambda_{3jk}''$  ( $j, k = 1, 2, 3$ ) in the process.

The total cross section for the process  $q_j \bar{q}_k \rightarrow \bar{t} \tilde{g}$  is:

$$\hat{\sigma}(\hat{s}) = \frac{1}{16N_c^2\pi\hat{s}^2} \int_{\hat{t}^-}^{\hat{t}^+} d\hat{t} \sum_{spins} |M|^2, \tag{2.6}$$

where  $\hat{t}^\pm = \frac{1}{2} \left[ (m_t^2 + m_{\tilde{g}}^2 - \hat{s}) \pm \sqrt{\hat{s}^2 + m_t^4 + m_{\tilde{g}}^4 - 2\hat{s}m_t^2 - 2\hat{s}m_{\tilde{g}}^2 - 2m_t^2 m_{\tilde{g}}^2} \right]$  and  $M$  is the amplitude. Here we have neglected the masses of incoming quarks.  $N_c = 3$  is the color factor and the bar over summation means averaging over the initial spins.

In a similar way, the cross section for  $\bar{q}_j \bar{q}_k' \rightarrow \bar{t} \tilde{g}$  can be calculated. The possible effects of  $q_j \bar{q}_k' \rightarrow \bar{t} \tilde{g}$  and  $\bar{q}_j \bar{q}_k' \rightarrow \bar{t} \tilde{g}$  should be observed in  $P\bar{P}$  or  $PP$  colliders. The cross section for the process  $P(P_1)P(P_2) \rightarrow (t + \bar{t})\tilde{g}X$  can be obtained by convoluting the subprocess with quark distribution functions [22],

$$\sigma(s) = \int dx_1 dx_2 f_i(x_1, Q) f_j(x_2, Q) \hat{\sigma}(\hat{s}, \alpha_s(\mu)) \tag{2.7}$$

with  $p_1 = x_1 P_1$ ,  $\tau = x_1 x_2 = \hat{s}/s$ .  $f_{i,j}(x_n, Q)$  ( $n = 1, 2$ ) are the corresponding quark distribution functions of protons. We take  $Q = \mu = 300$  GeV. Similarly we can find numerically the cross section of  $P(P_1)\bar{P}(P_2) \rightarrow (t + \bar{t})\tilde{g}X'$ .

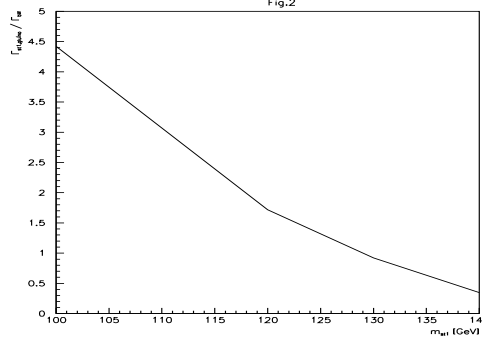


Figure 2: ratio of  $\Gamma_{\tilde{t}_1 \tilde{g}} : \Gamma_{bW}$  as function of mass of stop quark  $\tilde{t}_1$ , with  $m_{\tilde{g}} = 30$  GeV.

### III. Top and gluino decays

In the process of Eq. (2), we have in the final state two heavy particles which will possibly decay inside the detector. Here we will shortly review the relevant decay modes of the top quark and gluino [23, 24, 25, 26, 14].

The top decays in the MSSM have been considered by several authors [23, 24, 25, 26, 27]. The main decay mode is  $t \rightarrow bW$ , but  $t \rightarrow bH^+$  can compete with it if mass of the charged Higgs is lighter than  $m_t - m_b$ . Top quark decay to R-odd particles will also be important if those superparticles are light enough [27]. However, in our case, with heavy squarks, the decays to real superparticles are impossible, except for the light LSP gluino with light squark [13]. We plot the ratio  $\Gamma_{\tilde{t}_1 \tilde{g}} : \Gamma_{bW}$  as a function of the stop quark  $\tilde{t}_1$  mass,  $m_{\tilde{t}_1}$ , in Fig.2 for the gluino mass  $m_{\tilde{g}} = 30$  GeV. In order to guarantee the purported standard top quark events at the Tevatron,  $BR(t \rightarrow bW)$  should be larger than 40 – 50% as lower bound [28]. So with the assumption of light LSP gluino (about 25 – 35 GeV), lower limit on the mass of stop quark can be obtained. For the top quark decay through  $R_p$ -violating interactions [25], the branching ratio of those decay modes will be very small compared with  $t \rightarrow bW$  in our case. The only decay channel which we will consider in detecting top quark is the  $t \rightarrow bW \rightarrow b\nu_l$ , where  $l = e, \mu$ . We will confine us to these decays (with  $BR(W \rightarrow l\nu_l) \sim 22\%$ , its branching ratio in top quark decay should be at least 8.8 – 11%) since it is assumed that they have less background and are thus easier to detect than the hadronic decay modes.

We consider in this work a heavy gluino, which may be the LSP. The decay modes of a heavy gluino have been looked at e.g. in [14, 15] in  $R_p$  violating case. The decay channel  $\tilde{g} \rightarrow q\bar{q}$  will dominate if kinematically allowed. A lighter than squarks gluino will decay to

$$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_i^0, q\bar{q}'\tilde{\chi}_j^\pm, g\tilde{\chi}_i^0, \quad (3)$$

where  $\tilde{\chi}_i^0$  and  $\tilde{\chi}_i^\pm$  are neutralinos and charginos, respectively. The R-parity breaking decay modes become important for large  $\lambda''$ :

$$\tilde{g} \rightarrow q_i q_j q_k. \quad (4)$$

In Fig.3, we draw the  $\tilde{g}$  decay with parameters in mSUGRA model. We consider the decay of gluinos in Fig.3 (a) and (b) with  $R_p$  conservation and violation, respectively. In our calculations, only the two lightest neutralinos and the lightest chargino are considered, since the other

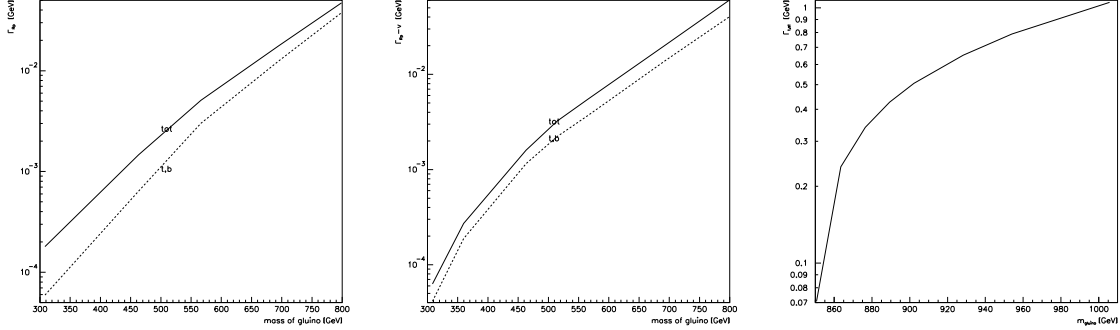


Figure 3: a) Decay width of gluino as a function of mass of gluino,  $m_{\tilde{g}}$ , for  $R_p$  conservation. Solid line corresponds to the total decay width and dashed line to partial width containing heavy quarks (top quark and bottom quark). b) Decay width of gluino as a function of  $m_{\tilde{g}}$  for  $R_p$  violation. Solid line corresponds to the total decay width and dashed line to the partial width containing heavy quarks (top and bottom). c) Decay width of gluino to  $t\tilde{t}_1$  as a function of  $m_{\tilde{g}}$ .

neutralinos and the heavier chargino are too heavy for gluino to decay into. It is shown that the gluino branching ratio to two heavy quarks (top quark or bottom quark) and neutralinos or charginos (or jets from  $R_p$ -violating interactions) can be very large and increases with mass of gluino. This is reasonable because stop quarks and sbottom quarks can be much lighter than the other scalar quarks due to the large Yukawa couplings. Especially, in  $R_p$ -violating terms, the process through virtual stop quark  $\tilde{t}_1$  will dominate the decay width because in the mSUGRA model it is the lightest squark and its mixing angle is near  $\pi/2$ . Thus, there are two  $b$  (or  $t$ ) quarks as a signal of gluino in our process (branching ratio can be read from Fig.3, as about 60 – 70%). Combined with other top quark, the three heavy quarks, leads to the final state  $3b + n(l + \nu)$  ( $n = 1, 2, 3$ ). This final state can be detected in the future CERN LHC and distinguished from background (with an assumed  $b$ -tagging efficiency  $\epsilon \sim 50\%$  in LHC [29]). For the much heavier gluinos which can decay directly to top quark and stop quark, decay width is shown in Fig.3 (c).

When gluino is the LSP, the only available decay modes are the R-parity violating ones. If the R-parity violating couplings are not exceedingly small, the gluino will decay in the detector through these channels. However, if the couplings are very small, the gluinos will form so-called R-hadrons before decaying (see e.g. [12, 13]).

#### IV. Numerical results

In the mSUGRA model we are interested in the region of the parameter space where the gluino is lighter than the squarks, with the possible exception of the lighter stop quark. This choice allows gluino to be produced via the third generation  $R_p$ -breaking coupling with relatively large cross section and on the other hand it is not complicated by gluino decay to other squarks than possibly the lightest stop.

As a representative example of this part of the parameter space, we take  $m_0 = 1000$  GeV,  $A_0 = -1000$  GeV,  $\tan \beta = 10$  and  $\text{sign}(\mu) = +1$ . Varying  $m_{1/2}$  suitably gives us the relevant gluino masses. The resulting masses for supersymmetric particles with the varied  $m_{1/2}$  are listed in

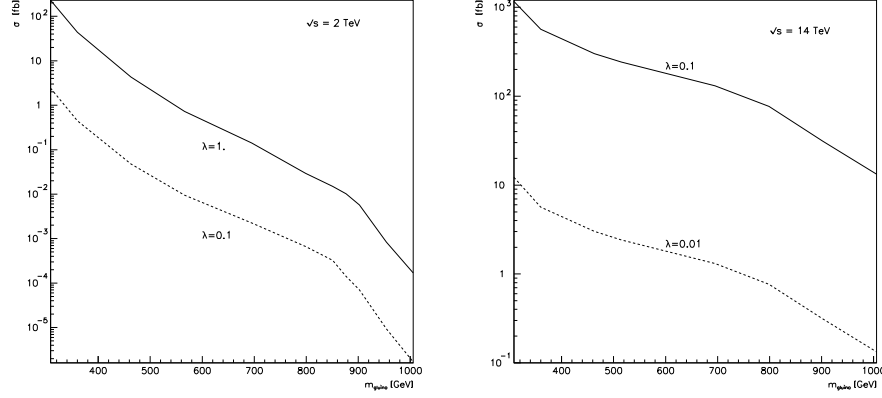


Figure 4: a) Cross section of  $P\bar{P} \rightarrow (t + \bar{t})\tilde{g}X$  as a function of  $m_{\tilde{g}}$  with  $E_{CMS} = 2$  TeV. Solid line corresponds to  $\lambda''_{3ij} = 1.0$  and dashed line to  $\lambda''_{3ij} = 0.1$ . b) Cross section of  $PP \rightarrow (t + \bar{t})\tilde{g}X$  as a function of  $m_{\tilde{g}}$  with  $E_{CMS} = 14$  TeV,  $\lambda''_{3ij} = 0.1$ .

Table 1<sup>1</sup>.

**Table.1** MSSM parameters with  $m_0 = 1$  TeV,  $A_0 = -1$  TeV,  $\tan\beta = 10$  and  $sign(\mu) = +$ , units of values are GeV in the table.

$m_{\frac{1}{2}}$	$m_{\tilde{g}}$	$m_{\tilde{t}_1}$	$m_{\tilde{t}_2}$	$m_{\tilde{b}_1}$	$m_{\tilde{q}}$	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_2^0}$
120	308	457	813	790	1020-1040	49	95
140	360	468	828	803	1028-1055	58	111
180	463	499	862	836	1060-1090	75	144
200	515	517	882	855	1075-1110	83	161
220	566	537	904	876	1100-1130	92	177
250	643	571	939	910	1120-1160	104	202
280	721	608	977	947	1160-1200	117	227
300	773	634	1004	974	1190-1230	125	243
330	850	675	1047	1016	1220-1270	138	268
340	876	689	1061	1031	1240-1280	142	277
350	902	703	1076	1045	1250-1300	146	285
370	954	733	1106	1076	1280-1330	155	302
390	1006	763	1138	1107	1310-1360	163	318

In Fig.4 (a), we show the cross section of  $P\bar{P} \rightarrow (t + \bar{t})\tilde{g}X$  as a function of mass of gluino ( $m_{\tilde{g}}$ ) at Tevatron Run II energy, i.e. with center-of-mass energy of the collision  $\sqrt{s} = 2$  TeV. There, the solid line corresponds to  $\lambda''_{312} = \lambda''_{313} = \lambda''_{323} = 1$  and dashed line to  $\lambda''_{312} = \lambda''_{313} = \lambda''_{323} = 0.1$ . At LHC with  $\sqrt{s} = 14$  TeV, the cross section for  $PP \rightarrow (t + \bar{t})\tilde{g}X$  as a function of  $m_{\tilde{g}}$  is shown in Fig.4 (b) with  $\lambda''_{312} = \lambda''_{313} = \lambda''_{323} = 0.1$  for solid line and  $\lambda''_{312} = \lambda''_{313} = \lambda''_{323} = 0.01$  for

<sup>1</sup>We thank A. Wodecki for providing us his program, which calculates the sparticle masses in MSSM. The program checks also some phenomenological constraints.

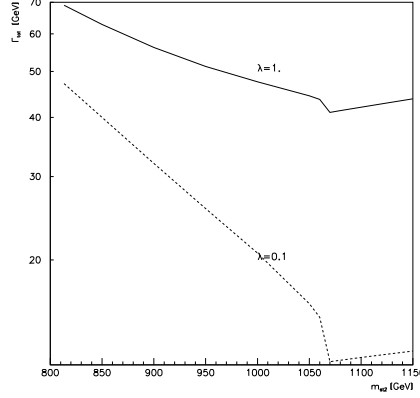


Figure 5: Decay width of stop quark  $\tilde{t}_2$  as function of mass of  $\tilde{t}_2$ . Solid line:  $\lambda''_{3ij} = 1.0$ . Dashed line:  $\lambda''_{3ij} = 0.1$ .

dashed line. In the calculations, we have neglected the decay width of  $\tilde{t}_1$ , since mass of  $\tilde{t}_1$  is far from the center-of-mass energy.  $\Gamma_{\tilde{t}_2}$  including  $R_p$ -violating contribution is shown in Fig.5, where solid line corresponding to  $\lambda''_{312} = \lambda''_{313} = \lambda''_{323} = 1$  and dashed line to  $\lambda''_{312} = \lambda''_{313} = \lambda''_{323} = 0.1$ . The results show that the cross sections can be very large if  $m_{\tilde{g}}$  is smaller than 400 GeV and  $\lambda''$  are close to the present limits ( $\lambda'' \sim 1$ ) in the Tevatron Run II (with luminosity about  $2\text{fb}^{-1}$ , it corresponds to hundreds of events). At LHC with luminosity  $30\text{fb}^{-1}$ , the process can potentially be seen with mass of gluino less than 1 TeV even if  $\lambda'' \leq 0.01$ .

We have also considered production of the LSP heavy gluino. It has been shown in the model of [13] that masses of gluinos below 115 GeV are excluded except a narrow window between  $m_{\tilde{g}} = 25 - 35$  GeV. We found that the cross section of the process in Tevatron Run I can be very large with masses of gluinos staying in that narrow window (about 10 pb with  $m_{\tilde{g}} = 30$  GeV,  $\lambda''_{3ij} = 1$  and all  $m_{\tilde{f}} = 150$  GeV). Unlike in the discussion of [13], gluinos can decay through  $R_p$ -violating interactions (e.g.  $\tilde{g} \rightarrow bcs$ ) if  $\lambda''$  is nonzero. The gluino decay added by single production of top-quark, should have been visible already in Tevatron Run I using above results. Therefore, the narrow LSP gluino window can give much stronger constraints on  $R_p$ -violating parameters  $\lambda''$  (with  $\lambda'' = 0.1$ , still several events are produced with luminosity  $19\text{pb}^{-1}$  in Fermilab), otherwise we can close this narrow LSP heavy gluino window.

In the mSUGRA model, the gaugino soft-SUSY-breaking masses are assumed to be equal at GUT scale and will lead to  $m_{\tilde{g}} : m_{\tilde{\chi}_1^\pm} : m_{\tilde{\chi}_1^0} \sim 7 : 2 : 1$  at low energy. However, there are other mechanisms such as O-II model [16] in which ratios of masses can be given as  $m_3 : m_2 : m_1 \sim -(3 + \delta_{GS}) : (1 - \delta_{GS}) : (33/5 - \delta_{GS})$  at GUT scale, where  $\delta_{GS}$  is the Green-Schwarz mixing term. Then at low energy, we can obtain light gluinos, which are almost degenerate with the lightest neutralino and chargino, with the heavy scalar quarks. As a representative of this model we take  $\delta_{GS} = -4.1$ ,  $m_0 = 1800$  GeV,  $m_{1/2} = 10$  GeV,  $A_0 = 0$ ,  $\tan\beta = 3$  and  $\text{sign}(\mu) = +1$  (leading to  $m_{\tilde{g}} \sim 102$  GeV and  $m_{\tilde{q}} \sim 1.5$  TeV). Setting  $\lambda''_{3ij} = 1$ , the cross section of the process  $P\bar{P} \rightarrow (t + \bar{t})\tilde{g}X$  can be about 3.6 fb with  $\sqrt{s} = 2$  TeV and of the process  $PP \rightarrow (t + \bar{t})\tilde{g}X$  about 27 pb with  $\sqrt{s} = 14$  TeV. So in this model the single production of



gluino can provide a very significant signal for detecting SUSY and  $R_p$  violation. Detecting pair production of gluino in this model was already discussed in [7, 11, 15] and it was shown that the  $R_p$ -violating decay of gluino will dominate if  $\lambda''$  are close to the present upper limits. Thus, the production of heavy quarks from gluino decay may provide a good signal for detecting gluinos. Similarly, when we detect the production of  $(t + \bar{t})\tilde{g}$ , we have at least two heavy quarks for tagging.

#### IV. Conclusion

We have studied the processes  $PP(P\bar{P}) \rightarrow (t + \bar{t})\tilde{g}X$  in supersymmetric models with explicit  $R_p$ -violation. We have seen that it is possible to test the models at future Fermilab Tevatron Run-II and CERN LHC experiments, provided the  $\lambda''$ -type couplings are large enough. We suggest also to check the old data in Tevatron Run I and get stronger constraints on  $R_p$  violation or exclude the narrow window of LSP heavy gluinos.

The process, with single production of top quark and gluino, can give signals both for SUSY and  $R_p$  violation. Specifically, in a typical O-II model, the process will be an important one to check SUSY and  $R_p$  violation. It is also shown that gluinos should be detected through their  $R_p$ -violating decay if  $R_p$  violating parameters  $\lambda''$  are close to the upper bounds.

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## Appendix

In this appendix we present the mass matrices [10] which we need in the calculations.

### A. The sfermion sector

In the mSUGRA model, the masses of squarks and sleptons follow from the GUT scale parameters  $m_0, m_{1/2}, A_0, \tan \beta$  and  $\text{sign}(\mu)$  [10]. The sfermion mass matrices are given by

$$M_{\tilde{f}}^2 = \begin{pmatrix} m_{\tilde{f}_L}^2 + m_f^2 & m_f(A_f - \mu r_f) \\ m_f(A_f - \mu r_f) & m_{\tilde{f}_R}^2 + m_f^2 \end{pmatrix}, \quad (\text{A.1})$$

where  $m_{\tilde{f}_{L,R}}$  are given in [10],  $m_f$  are the masses of the partner fermions and  $r_{d,s,b} = r_{e,\mu,\tau} = 1/r_{u,c,t} = \tan \beta$ . From these matrices we can get the mixing angles  $\theta_f$  and masses of the sfermions:

$$\sin 2\theta_f = \frac{2m_f(A_f - \mu r_f)}{m_{\tilde{f}_1}^2 - m_{\tilde{f}_2}^2}, \quad \cos 2\theta_f = \frac{m_{\tilde{f}_L}^2 - m_{\tilde{f}_R}^2}{m_{\tilde{f}_1}^2 - m_{\tilde{f}_2}^2}, \quad (\text{A.2})$$

$$m_{\tilde{f}_{1,2}}^2 = m_f^2 + \frac{1}{2} \left[ m_{\tilde{f}_L}^2 + m_{\tilde{f}_R}^2 \mp \sqrt{(m_{\tilde{f}_L}^2 - m_{\tilde{f}_R}^2)^2 + 4m_f^2(A_f - \mu r_f)^2} \right]. \quad (\text{A.3})$$

### B. The chargino/neutralino sector

In order to calculate the decay of gluino, we need to consider the chargino and neutralino mass terms. The general chargino mass matrix is given as follows [10]:

$$M_C = \begin{pmatrix} m_2 & \sqrt{2}m_w \sin \beta \\ \sqrt{2}m_w \cos \beta & \mu \end{pmatrix}. \quad (\text{B.1})$$

It can be diagonalized by two real matrices  $U$  and  $V$ ,

$$U^* M_C V^{-1}, \quad (\text{B.2})$$

where  $U = \mathcal{O}_-$ ,  $V = \mathcal{O}_+$  if  $\det M_C \geq 0$  and  $V = \sigma_3 \mathcal{O}_+$  if  $\det M_C < 0$ , with

$$\sigma_3 = \begin{pmatrix} +1 & 0 \\ 0 & -1 \end{pmatrix}, \quad \mathcal{O}_\pm = \begin{pmatrix} \cos \theta_\pm & \sin \theta_\pm \\ -\sin \theta_\pm & \cos \theta_\pm \end{pmatrix}, \quad (\text{B.3})$$

and

$$\begin{aligned} \tan 2\theta_- &= \frac{2\sqrt{2}m_w(m_2 \cos \beta + \mu \sin \beta)}{m_2^2 - \mu^2 - 2m_w^2 \cos \beta}, \\ \tan 2\theta_+ &= \frac{2\sqrt{2}m_w(m_2 \sin \beta + \mu \cos \beta)}{m_2^2 - \mu^2 + 2m_w^2 \cos \beta}. \end{aligned} \quad (\text{B.4})$$

Then the chargino masses are,

$$m_{x_{1,2}^+} = \frac{1}{\sqrt{2}} [m_2^2 + \mu^2 + 2m_w^2 \mp \{(m_2^2 - \mu^2)^2 + 4m_w^4 \cos^2 2\beta + 4m_w^2(m_2^2 + \mu^2 + 2m_2\mu \sin 2\beta)\}^{\frac{1}{2}}]^{\frac{1}{2}} \quad (\text{B.5})$$

In the case of the neutralinos, the mass matrix is given by [10]:

$$M_N = \begin{pmatrix} m_1 & 0 & -m_z s_w \cos \beta & m_z s_w \sin \beta \\ 0 & m_2 & m_z s_w \cos \beta & -m_z s_w \sin \beta \\ -m_z s_w \sin \beta & m_z c_w \sin \beta & 0 & -\mu \\ m_z s_w \sin \beta & -m_z c_w \sin \beta & -\mu & 0 \end{pmatrix}. \quad (\text{B.6})$$

It can be diagonalized by a unitary matrix  $N$  ( $4 \times 4$ ) as:

$$N^T M_N N. \quad (\text{B.7})$$

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